Four watt long-term stable intracavity frequency-doubling $Nd:YVO_4$ laser of single-frequency operation pumped by a fiber-coupled laser diode

Yaohui Zheng, Huadong Lu, Fengqin Li, Kuanshou Zhang,* and Kunchi Peng

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China

*Corresponding author: kuanshou@sxu.edu.cn

Received 13 April 2007; accepted 30 May 2007;
posted 1 June 2007 (Doc. ID 82095); published 12 July 2007

The longitudinal-mode stability of a single-frequency intracavity frequency-doubling laser can be enhanced by increasing the ratio between the nonlinear spectral bandwidth and the gain bandwidth of the laser. A 4 W long-term stable cw single-frequency green laser is obtained using an etalon inside the laser cavity as a spectral filter. No mode hopping is observed when the laser operates for 6 h and the power fluctuation is less than ±1.2%. In contrast, in the situation of no etalon inside the laser cavity, mode hopping can be observed at irregular intervals and the power fluctuation is ±3.8% when the laser operates for 4 h. © 2007 Optical Society of America

OCIS codes: 140.3480, 140.3570.

1. Introduction

Stable single-frequency lasers are important for high-resolution laser spectroscopy and precision metrology [1–3]. Several techniques have been developed to obtain single-frequency operation of lasers. Among them the unidirectional ring laser geometry is a robust and successful technique. High-power single-frequency green lasers using the ring cavity geometry have been reported by several groups [4–7]. To obtain a stable single-frequency laser, an etalon was inserted into the cavity to confine oscillation to the 1064 nm line [4] or 1061.4 nm line [5] and to prevent oscillation on other lines. In all of the above studies, however, the influence of γ (the ratio between the nolinear spectral bandwidth of the nonlinear crystal and the gain bandwidth of laser crystal) responsible for the mode stability was not considered. Recently, this kind of influence was investigated theoretically by Greenstein and Rosenbluh [8]. In a high-power intracavity frequency-doubling laser of single-frequency operation, the nonlinear conversion is a dominant loss for the fundamental wave. When the value of γ is less than a certain value, at certain wavelengths the nonlinear loss due to sum-frequency generation will be very small, and it might be that at these wavelengths the net gain is not depleted by the nonlinear loss and becomes positive, thus leading to multimode oscillation or mode hopping [8]. In this paper, we use an etalon of proper finesse and free spectral range (FSR) inside the cavity of a high-power intracavity frequency-doubling laser as a spectral filter to increase the value of γ; the multimode oscillation and the mode hopping are suppressed. Four watts of long-term stable single-frequency output at 532 nm is obtained.

2. Theory Analysis and Design of the Laser

For an intracavity frequency-doubling laser of single-frequency operation, the nonlinear conversion is a considerable loss for the fundamental wave. If one wants to obtain a long-term stable laser without multimode oscillation or mode hopping, the following equations should be satisfied [8]:

$$\frac{G_i}{2g_0(\tilde{\lambda}_i,\ 1)l} = \frac{1}{1+\dfrac{2S(\tilde{\lambda}_i)}{S_0(\tilde{\lambda}_i,\ 1)}} - \alpha(\tilde{\lambda}_i) - 2\varepsilon(\tilde{\lambda}_i,\ \tilde{\lambda}_i,\ \gamma)\frac{S(\tilde{\lambda}_i)}{S_0(\tilde{\lambda}_i,\ 1)} = 0, \quad (1a)$$

0003-6935/07/220001-04$15.00/0

$$\frac{G_i}{2g_0(\tilde{\lambda}_j,\ 1)l} = \frac{1}{1+\frac{2S(\tilde{\lambda}_i)}{S_0(\tilde{\lambda}_i,\ 1)}} - \alpha(\tilde{\lambda}_j) - 4\varepsilon(\tilde{\lambda}_i,\ \tilde{\lambda}_j,\ \gamma)\frac{S(\tilde{\lambda}_i)}{S_0(\tilde{\lambda}_i,\ 1)} < 0, \quad (1b)$$

where $\tilde{\lambda}_{i,j} = \lambda_{i,j}/\Delta\lambda_g$; λ_i and λ_j are the wavelength of lasing and nonlasing modes, respectively; $\Delta\lambda_g$ is the gain bandwidth; $\gamma = \Delta\lambda_{NL}/\Delta\lambda_g$; $\Delta\lambda_{NL}$ is the nonlinear spectral bandwidth; G is the net gain; g_0 is the small signal gain factor; l is the length of the gain medium; $\alpha = L/(2g_0 l)$; L is the total round-trip linear loss at the fundamental; $\varepsilon = (KS_0)/(4g_0 l)$; K is the factor of nonlinear conversion; S_0 is the saturation power; and S is the fundamental power.

Using the parameters of our laser ($L = 4.72\%$, $g_0 l = 0.1553P_{in}$, $S_0 = 0.136$, and $\varepsilon = 0.0094/P_{in}$, where P_{in} is the incident pump power) and Eqs. (1a) and (1b), the phase diagram (Fig. 1) for laser operation can be obtained. The area above the curve is the phase space in which the laser can operate in a single-longitudinal mode, whereas under the curve the laser operates in a multimode regime. It can be seen that for single-longitudinal-mode operation, the minimum allowed γ value is increased when the incident pump power increases.

In the laser we designed, $Nd{:}YVO_4$ crystal and LiB_3O_5 (LBO) crystal are used as the gain medium and nonlinear material, respectively. The gain bandwidth of the $Nd{:}YVO_4$ crystal is 255 GHz. The bandwidth–length product of the LBO is 226 GHz cm for second-harmonic generation under noncritical phase-matching conditions at 1064 nm. For a 1.8 cm length of LBO, the spectral bandwidth is 125 GHz and γ will be 0.493. According to the calculation (Fig. 1), it can be seen that when the maximum incident pump power is 15 W the laser can single-frequency operate stably. If we want to get a long-term stable laser of single-frequency operation at high pump power, some element should be used inside the cavity to narrow the gain bandwidth and increase the value of γ. As an example, when the pump power is 25 W (the maximum pump power of our pump source), γ should be 0.54, which can be obtained by inserting an etalon of proper finesse and FSR inside the cavity as a spectral filter.

In our experiment, an uncoated silica quartz plate with a thickness of 0.3 mm was used as the etalon so that the finesse (F) is 0.6 and the FSR is 343 GHz. The effective gain bandwidth with the etalon in the laser cavity is given by [9]

$$\frac{1}{\Delta\lambda_{eff}{}^2} = \frac{1}{\Delta\lambda_g{}^2} + \frac{F^2}{(\mathrm{FSR})^2(\eta + L)}, \qquad (2)$$

where η is the nonlinear conversion loss. Using the parameters of our laser (at a pump power of 25 W) and Eq. (2), the effective gain bandwidth is 130 GHz and γ is 0.96. Using this etalon inside the laser cavity, a long-term stable laser of single-frequency operation can be obtained at high pump power.

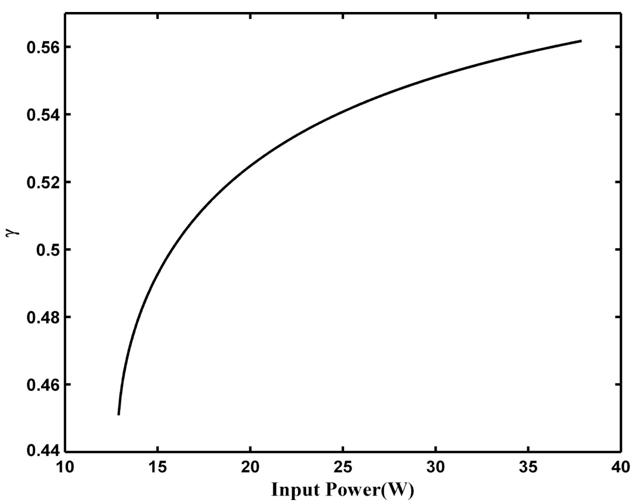

Fig. 1. Phase diagram of the ratio between the nonlinear spectral bandwidth and the gain bandwidth versus input power.

3. Experimental Setup and Results

The laser configuration is shown in Fig. 2. An 8-shaped ring resonator formed by four mirrors is designed. The input coupler M1 is a plane mirror with high reflection at 1.064 μm and antireflection at 808 nm; the cavity mirror M2 is a plane mirror with high reflection at 1.064 μm; M3 is a plano–concave mirror with high reflection at 1.064 μm and a radius of 100 mm; and the output coupler M4 is a plano–concave mirror with high reflection at 1.064 μm, high transmission at 532 nm, and a radius of 100 mm. The optical length between M3 and M4 is 120 mm and the rest of the optical length of the resonator is 390 mm so that the resonator stable condition of $|A + D| \leq 2$ can be satisfied. A 25 W fiber-coupled laser diode is used as the pump source. The diameter of the coupled fiber is 400 μm and the numerical aperture is 0.20. The laser diode beam is focused onto the $Nd{:}YVO_4$ crystal by the telescope system with a transmission efficiency of 94%. The dimensions and the Nd-doping concentrations of the a-cut $Nd{:}YVO_4$ crystal are 3 mm × 3 mm × 8 mm and 0.3 at. %,

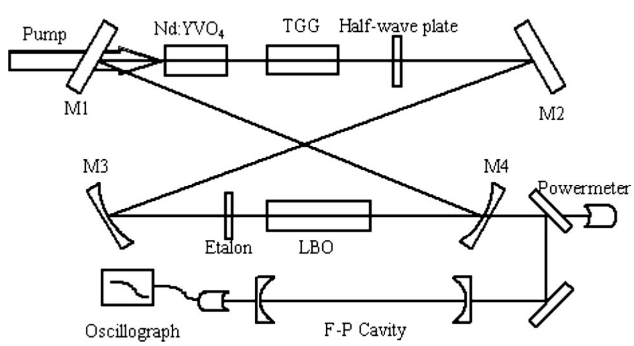

Fig. 2. Schematic of the intracavity frequency-doubling green laser of single-frequency operation.

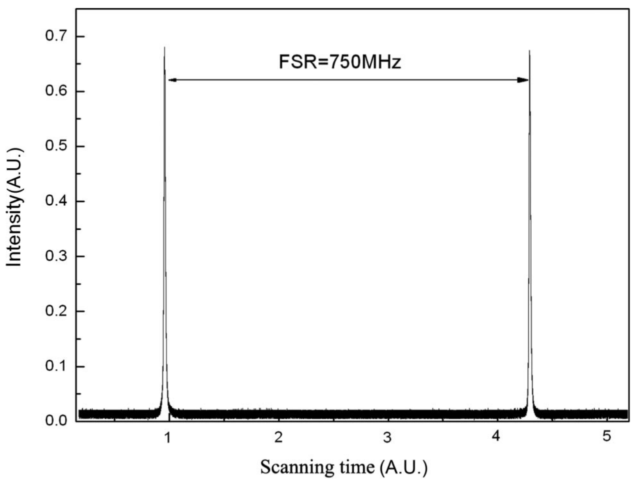

Fig. 3. Transmission intensity of the scanning confocal F–P interferometer; it indicates that the laser is in single-longitudinal-mode operation.

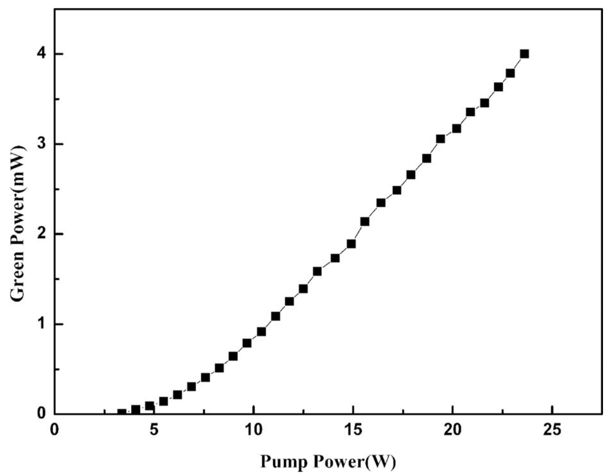

Fig. 5. Output power of the single-frequency green laser versus pump power.

respectively. Both end faces of the Nd:YVO_4 crystal are antireflection coated at 1.064 μm and 808 nm. A LBO crystal with dimensions of 3 mm × 3 mm × 18 mm is used as the nonlinear crystal that temperature controls the phase-matching temperature of 149 °C by use of a homemade temperature controller with the precision of 0.1 °C. A terbium gallium garnet (TGG) and a half-wave plate are used as an optical diode to enforce laser unidirectional operation. The etalon mentioned above is used in the laser cavity as a spectral filter. The etalon is temperature controlled by a homemade temperature controller in the range of 15 °C–70 °C with the precision of 0.01 °C. The output power is measured by a powermeter (FieldMaster from Coherent Inc., Santa Clara, California, USA). The longitudinal mode of the laser is monitored by a scanning confocal Fabry–Perot (F–P) interferometer (FSR is 750 MHz) and recorded by an oscilloscope (Agilent Infiniium 54830B, Santa Clara, California, USA).

In the case of no etalon in the laser cavity, when the pump power is less than 15 W, a stable single-frequency laser can be achieved. The transmission intensity of the scanning confocal F–P interferometer is shown in Fig. 3; it indicates that the laser is in single-longitudinal-mode operation. When the pump power is increased, multimode oscillation and mode hopping of the laser can be observed. Figure 4 is the laser output power stability at the pump power of 23.5 W, and the power fluctuation is $\pm3.8\%$ when the laser operates for 4 h. It can be seen that the fluctuation of the output power is larger and some step changes occur at irregular intervals. This can be explained by the fact that the value of γ is not large enough and the net gain of the nonlasing mode is not depleted by the nonlinear loss and becomes positive, so that the nonlasing mode cannot be suppressed and multimode oscillation or mode hopping of the laser occurs.

Then, the etalon we designed is used as a spectral filter in the laser cavity. It is ensured that the etalon

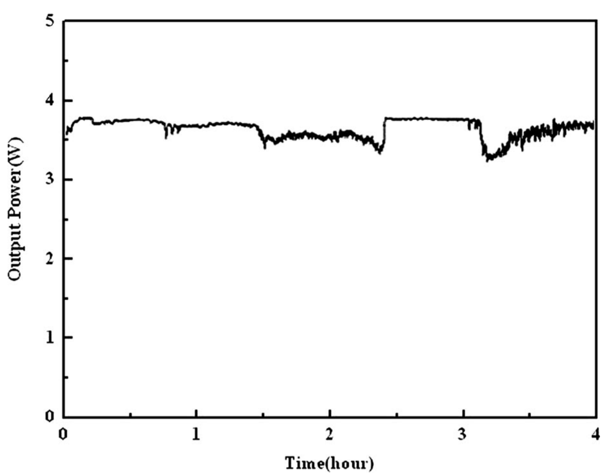

Fig. 4. Output power stability of the laser over 4 h without the etalon in the laser cavity.

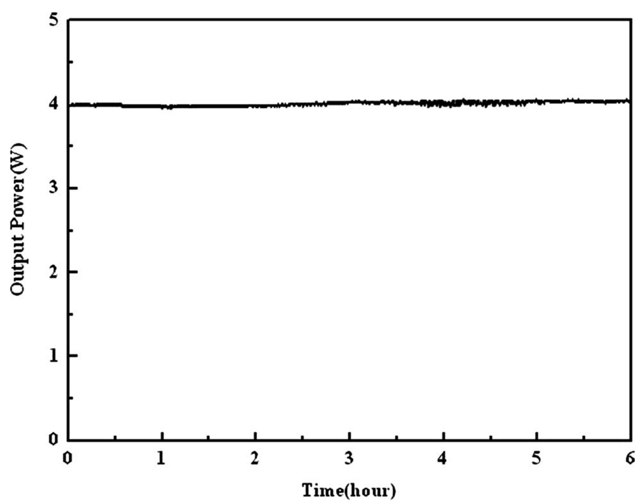

Fig. 6. Output power stability of the laser over 6 h with the etalon in the laser cavity.

resonance coincides with the laser cavity resonance at the peak of the gain curve by adjusting the temperature of the etalon to 40.2 °C. A long-term stable cw single-frequency green laser is obtained. The curve of the output power versus pump power is shown in Fig. 5. The maximum output power is 4 W at a pump power of 23.5 W. It can be seen that the output power increases monotonously with the input power. Figure 6 is the laser output power stability at a pump power of 23.5 W. The power fluctuation is less than $\pm 1.2\%$ when the laser operates for 6 h and no mode hopping is observed. The beam quality M^2 of the green laser is measured by a ModeMaster (Coherent Inc.). The measured values of $M_x^{\,2}$ and $M_y^{\,2}$ are 1.09 and 1.15, respectively.

4. Conclusion

In summary, a long-term stable intracavity frequency-doubling $Nd:YVO_4$ laser of single-frequency operation has been obtained by inserting an etalon of proper finesse and FSR inside the cavity as a spectral filter to increase the ratio between the nonlinear spectral bandwidth of the nonlinear crystal and the gain bandwidth of the laser crystal. The maximum output power of the single-frequency green laser was 4 W, the power fluctuation was less than $\pm 1.2\%$ when the laser operated for 6 h, and no mode hopping was observed. In contrast, in the situation of no etalon inside the laser cavity, mode hopping can be observed at irregular intervals and the power fluctuation is $\pm 3.8\%$ when the laser operates for 4 h.

This work was supported by the National Nature Science Foundation of China (60478007 and 60527003), the Program for Changjiang Scholars and Innovative Research Team in University, and New Century Excellent Talent (NCET-05-0265).

References

1. W. Q. Xi, J. Y. Zhao, and K. S. Zhang, "A high-power continuous-wave laser-diode end-pumped $Nd:YVO_4$ laser of single-frequency operation," Chin. Phys. Lett. **21,** 1532–1535 (2005).
2. M. V. Okhapkin, M. N. Skvortsov, A. M. Belkin, N. L. Kvashnin, and S. N. Bagayev, "Tunable single-frequency diode-pumped Nd:YAG ring laser at 1064/532 nm for optical frequency standard application," Opt. Commun. **203,** 359–362 (2002).
3. M. V. Okhapkin, M. N. Skvortsov, N. L. Kvashnin, and S. N. Bagayev, "Single-frequency intracavity doubled Yb:YAG ring laser," Opt. Commun. **256,** 347–351 (2005).
4. K. I. Martin, W. A. Clarkson, and D. C. Hanna, "3W of single-frequency output at 532 nm by intracavity frequency doubling of a diode-bar-pumped Nd:YAG ring laser," Opt. Lett. **21,** 875–877 (1996).
5. K. I. Martin, W. A. Clarkson, and D. C. Hanna, "Stable, high-power, single-frequency generation at 532 nm from a diode-bar-pumped Nd:YAG ring laser with an intracavity LBO frequency doubler," Appl. Opt. **36,** 4149–4152 (1997).
6. H. B. Wang, Y. Ma, Z. H. Zhai, J. R. Gao, and K. C. Peng, "1.5 W cw frequency-stabilized and intracavity frequency-doubled ring laser end-pumped by diode laser," Chin. J. Lasers **29,** 119–122 (2002).
7. Y. H. Zheng, H. D. Lu, F. Q. Li, K. S. Zhang, and K. C. Peng, "All-solid-state high-efficiency high-power $Nd:YVO_4$/KTP laser of single-frequency operation," Chin. J. Lasers **34,** 739–742 (2007).
8. S. Greenstein and M. Rosenbluh, "The influence of nonlinear spectral bandwidth on single longitudinal mode intra-cavity second harmonic generation," Opt. Commun. **248,** 241–248 (2005).
9. K. I. Martin, W. A. Clarkson, and D. C. Hanna, "Self-suppression of axial mode hopping by intracavity second-harmonic generation," Opt. Lett. **22,** 375–377 (1997).